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A report on an outreach program in nuclear science for high school students

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A REPORT ON AN OUTREACH PROGRAM IN NUCLEAR SCIENCE FOR HIGH SCHOOL STUDENTS

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ABSTRACT

A REPORT ON AN OUTREACH PROGRAM IN NUCLEAR SCIENCE FOR HIGH SCHOOL STUDENTS

by David E. Foster

A nuclear science summer school program for high school students was developed using high school teachers and college professors to conduct the course. Lecture materials consisted of topics including the atomic nucleus, fission, fusion, and nuclear medicine. Laboratories supported the lectures by having students complete half-life, thickness gauging, and food irradiation experiments. Computers were used for writing laboratory and research reports, and for analyzing data. Students toured local nuclear science facilities where they heard lectures from leaders in the field.

The program has been tested for two years at the San Jose State University Nuclear Science facility, and has received support from the numerous local nuclear national laboratories and talent in the area. Participants earned three college research units from the Department of Chemistry at San Jose State University. Students and instructors considered the program to be effective, its popularity shown by numerous requests for reservations, and the necessity to offer multiple sections in 1997.

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Thesis statement: The teaching of nuclear science is underrepresented at the high school level. There is a need to involve high school science teachers in programs that will provide them with the instructional materials, experience, and confidence to teach the important diversified concepts found in nuclear science.

CHAPTER 1

SECTION 1 - INTRODUCTION

Greater emphasis should be placed on nuclear science education at the high school level. Nuclear science impacts such diverse fields as material science, engineering, chemistry, physics, environmental and biological science, archeology, and geology. The cross-curricular nature of nuclear science provides a natural bridge among these diverse fields. Developing teaching strategies and techniques for nuclear sciences can provide teachers with effective methods for presenting science education. The use of nuclear science continues to proliferate in nearly all areas of science and technology. When students are provided a broad overview of topics and experimental techniques in nuclear science, they will gain a better foundation for making future educational choices and selecting a field of study.

Examples of the cross-curricular connections of nuclear science are abundant. Chemistry and physics units include the atomic structure, quantum theory, nuclear structure, binding energy, modes of decay, fission, fusion, and the laws of conservation of mass/energy. Engineering and material sciences use radioactive isotopes to track pipe leaks and utilize x-ray crystallography to visualize stress cracks. Radioactive tagging and doping are used to monitor wear-resistant properties of friction-bearing surfaces.[1] Biological and environmental sciences utilize radioactive isotopes to check the action of fertilizers in plants and the progress of food in digestion.[2] Archeology uses carbon dating for establishing the ages of objects containing carbon such as wooden artifacts and bones. In geology, uranium dating helps to establish the age of rocks and sediments.[3]

Several teaching methods can be utilized to introduce students to nuclear science. Lectures, guest science speakers, field trips, research papers, and projects are several techniques used to explore nuclear science concepts. In addition, students learn a variety of laboratory procedures which include instrumental analysis, quantitative analysis, statistics, and safe handling methods to prevent the risk of cross-contamination. There are multiple computer-based applications in nuclear science. For example, computer-based laboratories in experimental design and experimental data analysis use interactive programs which simulate actual results.

Nuclear science plays a significant part in today's society. Radiation is used to induce chemical reactions, probe atomic, molecular and material structure, induce ionization, and ascertain transmission and attenuation measurements. Radionuclides are utilized as chemical markers and as a source of radiation. Nuclear reactions are used to change properties of substances as well as elemental analysis. Examples of the prevalence of nuclear science are given below.

Medicine

Radiation has long been used in medicine as a diagnostic and therapeutic tool. Imaging techniques have been used for over one hundred years to noninvasively visualize internal features of the body. X-rays have been used since 1895 for visualizing bones and other regions of the body. The x-rays scatter more strongly off denser regions of the body,[4] thereby attenuating the intensity of the radiation. This attenuation is measured by exposing photographic film to the radiation that passes through the body. The degree of exposure is a measure of the density of the tissue, and this provides an image of the body. Position emission tomography (PET) and magnetic resonance imaging (MRI) are two other common imaging techniques used in medicine. Each technique uses a different nuclear process to elucidate internal features of the body. These techniques can provide more detailed images than simple x-rays.[5]

Deposition of radiation on localized areas provides a method of killing very specific and potentially damaging cells, such as malignant tumors. The radiation deposits large amounts of energy over a very short range. Modern techniques and drugs allow the radiation to interact more strongly with the damaged tissue. The large energy deposition induces significant chemical reactions, causing a destruction of the biological activity of the cancerous tissue.[6]

Public Safety

Radioactivity is used in various detection devices to support public safety. Manufacturers of railroad tracks use gamma rays to detect internal flaws. Airline maintenance companies and manufacturers use gamma rays to find microcracks and to detect metal fatigue.[7] Neutron activation analysis and x-ray fluorescence are used for inorganic elemental analysis of high technology materials and forensics. Many smoke detectors contain small amounts of radioactive isotopes which ionize air molecules. The ions conduct an electric current inside the smoke detector in which a sensing device monitors the current. Any interaction of smoke particles and radiation reduces the electric current and sounds the alarm.[8]

Law enforcement and airport security use detection technology similar to medical computer tomography, or CAT scan. Some machines can map objects within luggage and identify explosive devices.[9]

Food Sciences

The food science industry has long used radiation to preserve food products and kill harmful bacteria. Food products spoil when they are infested with fungi, parasites, and insects. Salmonella and E. coli bacteria, commonly found in chicken and beef, can make people dangerously ill and may even cause death. These organisms are especially dangerous for the very young and very old and those with suppressed immune systems.[10] The gamma rays from ^{137}Cs and ^{60}Co kill the infestations and harmful bacteria, preserving the chicken and beef, making the meat safe to eat.

Industrial Applications

Industry uses radiation in the production of energy and for quality control during manufacturing. During production, radiation is used to measure the proper thicknesses of metal sheets, plastic wrap, and other products. The thickness of the stock is controlled by radioactive isotopes. Radiation intensity measurements are recorded by a computer which makes adjustments to control the thickness.[11] Engineers test engine wear by making the cylinder walls in the engine radioactive. The piston rings rub against the cylinder walls of the running engine and the worn away radioactive metal falls into the lubricating oil. With a radiation detector, an engineer can determine which oil provides the least wear to the engine.[12]

Industry uses nuclear fission reactors to generate about 20% of electric energy in the United States. A single kilogram of uranium produces more energy than thirty freight car loads of coal. Fission reactors are thus an efficient method of producing energy.[13]

Geology and Archaeology

Geologists and archaeologists use the half-lives and activities of radioactive nuclides to determine the age of rocks, fossils, and artifacts. Archaeologists primarily use ^{14}C to determine the age of fossils, relics, artifacts, and monuments of past human life and activities which contain carbon. A geiger counter detects the radioactive ^{14}C atoms. The atoms are then measured and compared to the activity of a sample of similar material whose age is known. ^{14}C was used to determine that the Iceman is 5,715 years old.[14]

Geologists use uranium dating to calculate the age of nonliving things. Rocks can be dated by calculating the half-life of the uranium isotopes and the percentage of lead isotopes in the rock: the greater the percentage of lead isotopes, the older the uranium-bearing rock.[15] Such measurements provide our best estimate for the age of the earth.

The Need for Nuclear Science Education

Even though the use of nuclear science has increased during the past half century, high school students have had little exposure to the subject. Also, many high school teachers lack the experience and confidence to teach basic concepts. This problem is not new; it was recognized over thirty years ago that nuclear science has been ignored in the high school curricula. Revised below are segments found in the book Education and the Atom, written by Glenn Seaborg in 1964.

> Secondary school science classes tend to have poor nuclear science coverage, with very little laboratory equipment available.[16] High school teachers are often inexperienced in the use of nuclear equipment, their knowledge having been obtained primarily from descriptive material. The teacher may be isolated and out of contact with the nuclear science environment.[17]

The same conditions that existed in 1964 persist today: high school instructors are not prepared to teach the subject, and textbook coverage of nuclear science is poor. Recent studies of high school and freshman college chemistry texts show that nuclear science has limited coverage and are often the last chapters of a text! As a result, not only is the subject not included in laboratory settings, it is frequently omitted from lectures.

Foster[18] performed a study of seven general high school chemistry textbooks published since 1990. He found that chapters on nuclear chemistry constituted 3% of the page count, and were found in the last 4% of the book. One exception to this placed nuclear science in the beginning 25% of the text.

Foster's study was supported by Charles Atwood,[19] University of Georgia, who examined this issue at the college level, reviewing freshman chemistry textbooks used during the past seventy years. His 1990s study of ten textbooks showed that 4% of the page count was devoted to nuclear science and that these pages were located in the last 17% of the book. He noted that there has been a trend since the 1950s for the material to move further back in the book. Professor Elizabeth Klepinger supports these findings. During a lecture at the March 1996 American Chemical Society

National meeting in New Orleans, University of Kentucky Chemistry Professor Klepinger stated, "Where nuclear and radiochemistry have proliferated during the past two decades, exposure of students to this area of science has declined. Due to the lack of nuclear science instructional materials for high school students and teachers, instructors at the University of Kentucky are preparing nuclear science modules, targeting high school curriculum."[20]

"Outreach programs" are another way of introducing students to nuclear science. Literature searches were conducted[21-30] and programs exclusively concentrating on nuclear science could not be found. Several programs were identified that included some information about nuclear science in the curriculum.

The University of Washington established a program where undergraduates traveled to over forty high schools and led discussions on the environment. The effects of Chernobyl were among the topics of discussion.[31]

Purdue University in Indiana has used vans to facilitate high school students' use of instrumentation and equipment and to promote awareness of chemistry. In order to use the van "Chemobile," teachers must attend five weeks of workshops over two summers, and develop experiments utilizing the instrumentation provided. Following the workshops, the Chemobile is available as a lending library of instruments for teachers who have participated in the project. Students are given an opportunity to use simple counting equipment.[32]

The High School Faculty Institute for Chemistry Teachers, at Sacred Heart University in Connecticut, was established to provide continuing education for area high school chemistry teachers by exposing them to current topics in chemistry. A unit on radioactivity was included in this program.[33]

Many possible explanations exist for the apparent neglect of nuclear education at the high school level. Most science teachers have had limited education in this area. They lack the experience, the confidence, and the instructional materials to teach nuclear science concepts. In addition, nuclear science is generally considered synonymous with nuclear power, and the public has a strong bias against the nuclear power industry. There is also concern about the storage and transportation of nuclear waste and accidents that might occur. When nuclear science is discussed in the classroom, it is often negative, promoting fears such as those related to problems created by Chernobyl and Three Mile Island. The general public views nuclear science as a threat. They are often unaware of the benefits of nuclear technology and how it can improve the quality of life.

In order to change some of these misperceptions and to introduce students and teachers to the valuable concepts in nuclear science, a two-week, seventy-five-hour outreach program was developed at San Jose State University. The goal was to introduce students and teachers to nuclear science, providing high school teachers with the opportunity to gain the necessary experience in preparing nuclear science lectures and laboratories.

This training gave teachers a broader understanding of nuclear science applications and the confidence to build these concepts into their high school curricula. Students who participated in the program were exposed to a broad field of study which better prepared them for their college courses.

SECTION 2 - OVERVIEW OF THE COURSE

The summer program provided students with a global view of nuclear science. It incorporated elements of a good educational program including lectures by college and high school instructors and nuclear specialists working in the field. Other major components of the class were laboratory experiments, library research, data analysis and computer experience, tours, and individual study.

Lectures were presented by a variety of instructors. These lectures highlighted basic concepts of radioactivity and radioactive decay, environmental and anthropogenic sources of radioactivity, and applications of radiation and radioactive materials.

Tours and guest lecturers provided students and teachers with a "reality check." Classroom and laboratory experiences were supplemented with trips to several companies and national laboratories, including tours of the General Electric Nuclear Power Training Center (San Jose, California), Stanford Linear Accelerator, (Palo Alto, California), and Vallecitos Nuclear Facility (Pleasanton, California). Lectures from experts in the field were provided on all of the tours.

Laboratory experiments supplemented the classroom experience and provided students with practical knowledge of instrumental measurements. All experiments were derived from the upper division undergraduate nuclear science program at San Jose State University. Students used computers to analyze data from all experiments. Three formal laboratory reports were required.

Individual study was promoted as instructors gave assistance and instruction in the methods of library literature research. Students explored a relevant topic in nuclear science, summarized their work in a formal paper, and made an oral presentation on the final day of the course.

Upon successful completion of the program, participants earned three units of upper division research credit from the Department of Chemistry at San Jose State University.

The program gave high school teachers the opportunity to teach nuclear science and to obtain nuclear science course materials. They gained experience in lecturing and conducting nuclear science laboratories in front of their own students in a university setting. Instructors were provided with nuclear science educational materials that were transportable, age-level appropriate, and ready to be used in the classroom. These high school teachers plan to integrate additional nuclear science concepts into their existing high school science curricula and to teach future nuclear science summer school programs.

The summer program has run successfully for two years with one high school instructor and students from one high school participating in the pilot program. The program expanded during the second year to include students from four high schools and one additional high school instructor.

CHAPTER 2

LECTURES

Lectures were designed to provide students with a broad foundation in nuclear science. The course began with an overview of the atom and the atomic nucleus, focusing initially on concepts and nomenclature necessary to support the laboratory experiments. Students learned about nuclear transformation and processes whereby the nucleus emits charged particles so as to move to a more stable state. Nuclear reactions, including nuclear fusion and fission, showed students how higher-energy nuclear transformations can occur. These lectures on "pure" topics were balanced with extensive discussions on the applications of nuclear chemistry. Some examples included energy generation through nuclear power, thickness gauging techniques in industry, use of radionuclides for visualization in medicine, and the extensive applications in analytical science. The course concluded with lectures on natural and anthropogenic sources of radioactivity in the environment.

Atomic Nucleus and Radioactivity

The course began with a review of basic nomenclature, including the definitions of isotopes, strong force, atomic mass number, atomic number, protons, neutrons, and isobars. Lessons were divided into sections which focused on the concepts of stability and radioactivity, half-life, radioactive decay, energy released in decay, the penetrating power of radiation, and dating techniques.

Stability of a nucleus and radioactivity were explored through concepts of isotopes, decay modes, and half-lives. Isotopes are two forms of the same element, having the same number of protons, but a different number of neutrons. Different isotopes of a particular element thus have different atomic masses.[34] The three isotopes of hydrogen were given as an example. Each hydrogen nucleus has a single proton that defines the chemical properties of the atom. The mass of the atom is changed by the different number of neutrons, but its chemical properties are not changed.[35] Students learned that some isotopes are unstable. The unstable isotopes undergo a spontaneous change, usually by ejecting a beta particle, or in some nuclei, an alpha particle. The rate that the isotope decays is defined by the half-life. Half-life is the time required for half the atoms of a radioactive isotope of an element to decay. Tritium, an isotope of hydrogen having one proton and two neutrons, was given as an example. Tritium beta decays by effectively converting one of its neutrons into a proton, forming ^3He. The half-life of tritium is 12.6 years.

To demonstrate the concept of half-life, the class visualized a student jumping half way to a wall which was six feet away, then jumping half of the remaining distance, and continuing this process until they reached the wall. The class determined the number of jumps required. It was explained how this concept related to half-life and radioactive decay and how, at some point, all the radioactive atoms in a sample undergo decay.[36]

Distinctions were made between alpha particles, beta particles, and gamma rays. An alpha particle was defined as nucleus of a helium atom. Alpha particles are ejected by heavy elements with large amounts of kinetic energy.[37] Beta particles are simply electrons that do not exist as such in the nucleus, but are generated at the instant of beta decay. Gamma rays are "electromagnetic radiation which is partly electric and partly magnetic and carries energy emitted by vibrating electric charges in atoms."[38]

In order to understand how energy is released in decay, students should be able to compute the energy flow and the probability of nuclear reaction in order to determine the degree to which it will proceed. The symbolic way of writing atomic equations was demonstrated by writing transmutation formulas on the board as students followed along, using the periodic table. For example, the class wrote the formula for the alpha decay of ^{238}U (which becomes ^{234}Th) and then for the beta decay of ^{234}Th (which becomes ^{234}Pa).[39] Discussions also included exoergic and endoergic processes. If a reaction releases energy, it is exoergic; if the reaction requires energy, it is endoergic. Most kinds of induced nuclear reactions are endoergic. During radioactive decay, radiation is emitted to achieve a lower energy state and the reaction is therefore exoergic.[40]

There are great differences in the penetrating power of the three types of radiation. Alpha particles penetrate the least and can be blocked by paper. An alpha particle is easy to stop because it is relatively slow and its double-positive charge interacts strongly with the molecules it encounters. Beta particles are faster than alpha particles, and they can be blocked by aluminum. The beta particle carries only a single charge, and travels much faster through the air. Most beta particles lose their energy during the course of many near collisions with atomic electronics. Gamma rays are most penetrating of the three because they have no charge. With no electrical attraction or deflection, gamma rays interact with the absorbing material only by direct hit with an atomic electron (rarely with a nucleus) and can be blocked by lead. The class discussed how a magnetic field would cause alpha and beta particles to travel in a curved path while having no effect on gamma rays. Use of the magnetic field was then extended to introduce the concept of mass spectroscopy.[41]

The lesson on the applications of radioactivity focused on the use of radioactive decay to calculate the age of organic matter, rocks, and the solar system. The decay of a radionuclide is basically unaltered by temperature, pressure, chemical form, or other natural physical phenomena.[42] Chemical environments can have a minor impact on the half-lives of nuclides that decay by electron capture. A discussion was held on how carbon-14 was used to determine the age of biological artifacts and uranium was used to date inorganic artifacts.[43] The use of radiation in the fields of agriculture, medicine, and engineering was also explored.

Mass and Mass Energy Equivalence

The fact that "mass is energy" was the sole focus of lectures in this unit. Instruction was divided into sections which included Einstein's formula, variation of mass, separation of ions using a mass spectrometer, fission, fusion, and the charade of cold fusion.

The finding that mass equals energy is the most remarkable insight of Einstein's special theory of relativity. Einstein proposed the relationship $E=mc^2$ where E is the energy, m is the mass, and c represents the speed of light (900,000 km/s). Mass of a body is a measure of its energy content. When the energy content is changed by an amount E, the mass changes by an amount E/c^2. Mass is equivalent to energy, and that mass is a measure of the energy content of an object. The formula $E=mc^2$ expresses the important distinction that energy is equivalent to mass.[44]

The equivalence of mass and energy helps people understand why large amounts of energy are released in nuclear reactions. Mass and energy are basically the same; mass can be thought of as "squashed-up energy." The variations of mass were explained by showing how nuclear mass increased with increasing atomic number, and how the nuclear mass varies within an isobar.[45] Nuclear reactions occur when the transformation of one nucleus to another decreases the total mass of the nucleus.

Isotopic masses of various elements can be accurately measured with a mass spectrometer. This process of the separation of isotopes illustrates how isotopes are ionized and then aimed into a magnetic field where they are swept into semicircular tracks. Because of inertia, heavier ions travel as large radii, and lighter ions travel as smaller radii.[46] The mass spectrometer was historically used to verify the validity of $E=mc^2$.[47]

Nuclear fission is defined as "the process of splitting a heavy nucleus into two lighter nuclei. This process is most significant for actinides such as ^{235}U accompanied by the release of much energy." An example of the fission process requires the absorption of a neutron by a uranium nucleus. This neutron capture initiates the fission process producing two smaller nuclei and two to three additional neutrons. These additional neutrons are then free to interact with other uranium nuclei creating a chain reaction. The enormous amounts of energy released by one atom of uranium were compared to the equivalent amount of energy released by the explosion of seven million TNT molecules. Isotopes ^{235}U and ^{238}U were compared, and a discussion was held on how these isotopes related to critical mass. Harnessing energy from uranium isotopes to generate the electric energy in nuclear fission reactors in electric power plants, and the problems related to safely disposing of waste products were reviewed. An explanation was given as to how ^{239}Pu and ^{238}U produce abundant energy in breeder reactors. Also, the benefits and drawbacks of fission power were considered.[48] During the discussion of the famous Manhattan Project, it was explained how the atomic bomb got its energy from fission.[49]

Nuclear fusion was defined as "the combining of nuclei of light atoms, such as hydrogen, into heavier nuclei accompanied by the release of much energy."[50] For over 30 years, physicists have been working on the use of nuclear fusion to obtain power. One of the systems studied was the magnetohydrodynamic (MGD) generator in which the fusion reaction is confined by magnetic means. Another system studied involved laser fusion which is based on the ignition of a pellet of solid hydrogen containing deuterium and tritium by focused laser beams.[51]

Finally, the distention between the controversial cold fusion charade presented by professors Fleishman and Ponds in 1989 was examined. Cold fusion, which is muon-induced, does not require the high temperatures of the other techniques. Muons, however, are unstable and have half-lives of approximately two microseconds. At this time, the energy needed to produce muons is greater than the energy they release.[52]

Data Collection and Instrument Reliability

The concept of the measurement having an uncertainty can be illustrated by the use of frequency distribution curves. Uncertainty is often represented in statistics by a quantity called the standard deviation or the related variance. The amount of uncertainty is a measurement of the width of a distribution. There is less uncertainty about the mean of a narrow curve than for that of a broad curve. Therefore, when collecting data, an instrument with a narrow distribution is more reliable. Results can be quantified within a range of uncertainty when the variance or standard deviation is known.[53]

Statistics were presented to the students in terms of how data should be collected as normally-distributed values. An in-class demonstration showed that this was not always the case. Each student was asked to pick three numbers between one and twenty. Plotting the numbers in a time distribution and a frequency distribution showed that the numbers were not evenly distributed. The results were then applied to instrument performance, with an emphasis on the effects of a broad frequency distribution and artifacts in the time distribution. The lecture on statistics ended with a discussion of systematic errors, using as an illustration a long, hot shower perturbed by rapidly changing cold water pressure or decreasing the availability of hot water.

Food Irradiation

Students were presented information about the effect of ionizing radiation on matter, and how this process was used in the preservation of food products. The "Food Irradiation Lecture" examined how radiation can stop mold growth, retard sprouting, and slow the ripening process. A discussion was included on bacterial contamination and food poisoning. One reason that food spoils is the action of bacteria. Some bacteria are naturally present in food. Many people who eat spoiled food or some strains of bacteria get food poisoning. This food poisoning can be prevented by preserving food by gamma radiation.

CHAPTER 3

LABORATORY EXPERIMENTS

Note: See Appendix for laboratory introductions and procedures.

Laboratories were designed to support the lectures and to provide students with hands-on experience in the use of instruments and laboratory equipment. Experiments were performed in the areas of radiation emission and absorption, radiation detection, quantitative analysis, food irradiation, bacteria cross-contamination, and statistics.

Radiation Emission and Absorption

Cloud Chamber

The "Cloud Chamber Experiment" allowed students to visualize the ionization of a gas by radioactive emission. The students placed a piece of uranium and a magnet in the chamber saturated with alcohol, and then placed the chamber on dry ice. High energy particles ionized the air. The alcohol vapor condensed on the ions, leaving a vapor trail showing the path of the emission. The difference of the alpha and beta particles and gamma rays could be distinguished by the distance they traveled and the paths the particles took, due to the polarity of the magnet. The alpha particle, having a double positive charge, travels the shortest distance because of the great interaction with the vapor molecules. It takes a curved path due to the magnetic field. The beta particles, having a single negative charge, travel a longer distance than the alpha particles. Beta particles have less interactions with vapor molecules, and their path bends the opposite direction of the magnetic field. Gamma rays, being electromagnetic radiation, have no charge. They travel the longest distance, and they continue on a straight path, regardless of the polarity of the magnet.

Distance $1/r^{\wedge 2}$

The "Distance $1/r^{\wedge 2}$ Laboratory" helped students determine that a source of radiation will have a specific activity at different distances, and that the intensity of radiation decreases with distance. For a point source of radiation and a detector with a point geometry, the intensity should vary as the inverse square of its distance. The "Distance $1/r^{\wedge 2}$ Laboratory" allowed students to observe how the radiation intensity decreased as a function of distance. A source was placed a small distance away from the detector and the ionizing radiation was counted. The measurement was then repeated as the source-to detector distance was varied. Students analyzed the data by graphing the count rate versus $1/r^{\wedge 2}$, which resulted in a linear plot when the inverse square law was valid.

Thickness Gauging

As students completed the "Thickness Gauging Laboratory," they determined how the intensity of radiation changed as it passed through an absorber. Several measurements were taken using different thickness absorbers. Paper was used as a standard absorber. Beta particles were scattered away from the detector as they passed through the absorber, thus changing the detected beam intensity. Students graphed the results to show the exponential attenuation of the intensity.

Students also learned how to use the exponential attenuation plot as a calibration curve for intensity studies. A sample of an unknown thickness of paper was used as an attenuator. Students determined the intensity of the radiation that passed through the unknown. They then used the attenuation plot to determine the thickness of paper in the unknown sample.

Experimental designs were optimized by using successive approximation techniques. The intensity of radiation that passed through the unknown was measured first. Students measured the radiation intensity for an arbitrary number of pieces of paper. The initial result was used to determine the quality of the results. If the intensity was too low, there were too many sheets of paper. If the intensity was too high, there were too few sheets of paper. Students used their analysis to estimate the number of pieces of paper in the unknown. A new measurement was performed using the new estimate. Results were analyzed and the process was repeated until a proper estimate for the unknown thickness was decided. Post laboratory discussions illustrated how the thickness gauging could be applied to an industrial process.

Radiation Detection

Geiger-Müller (G-M) Working Region

An individual must understand the characteristics of a G-M detector along with the limitations to ensure the best results while using the instrument. At low voltage, the tube is operating in an area of potential, known as the recombination region; at a high voltage, the tube is operating in an area called the region of continuous discharge. In these two regions, the instrument's count rate at different voltages is very unstable. The voltage that falls in between these regions is considered "the working region," or the voltage at which the instrument should be operated. Across this voltage range, the count rate forms a plateau where the count rate is least sensitive to changes in voltage. During the G-M experiment, the students recorded pulse height versus voltage in order to determine the different counting regions of a gas-filled tube. Using this procedure, students were able to establish the plateau region which they will use when performing additional experiments.

Dead Time

When the students completed this laboratory, they learned that the performance of instruments can degrade as the radiation intensity increases. Dead time refers to the amount of time needed for the detector to recover from one ionizing event to the next ionizing event. Lost counts between ionizing events occur because the counter requires a finite time to process an event at which time no other events can be accounted for, and the counter is said to be dead. The minimum time interval between two events is called the resolving time, and the correction for this is calculated using the paired source method. This method involves comparing the data collection rates for the combination of two radioactive sources to that of the sum for individual data collection rates. Paired radioactive sources were used to illustrate instrument dead time. The correction of the dead time is calculated using appropriate equations.

Quantitative Analysis

Volume Determination

The "Unknown Volume Determination Laboratory" allowed the student to measure the change of specific activity of a sample upon dilution and to use the dilution factor to determine the volume of liquid in a container. Liquid scintillation fluor was placed in a container with an unusual shape. The ^{3}H or ^{14}C standards were used. A small predetermined volume of solution was extracted from the reservoir and its activity determined (SA_1). Then an equivalent volume (V_1) of a "spike" with a known specific activity was added to the reservoir stand, thoroughly mixed. A sample was then extracted, its activity determined, and then subtracted from the initial activity, giving (SA_2). The unknown volume (V_2) was determined from the following: $V_1A_1 = V_1A_2$.

Half-life

The students completed an experiment related to age-dating, based on radioactive decay rates of radioisotopes. This "Half-life Laboratory" allowed the students to extract the half-life of a nuclide in the presence of background radiation and a short-lived nuclide. Students were shown how to remove the background from the data and to determine the two half-lives. A neutron generator was used to bombard silver foil to produce different isotopes of silver, having different half-lives.

Statistics

Frequency Distribution

The "Frequency Distribution Activity" illustrated the statistical nature of radioactive decay and allowed students to determine the instrumental uncertainty in their measurements. Students made multiple measurements on the activity of a long-lived radionuclide. Up to four hundred such measurements were analyzed through time and frequency distributions, using standard scientific graphics software. The students used the graphs to observe the Gaussian nature of the data, deviations from this distribution, and to compare the performance of different instruments.

Food Irradiation - Bacteria Cross-contamination

Food Irradiation

The "Food Irradiation Laboratory" was designed to demonstrate the use of ionizing radiation on matter by showing the benefits of ionizing radiation on food products. Students planned a lab where they observed the effects of irradiation on their assigned food. Examples of irradiated foods that have potential for bacteria and pests are cheese, bread, tortillas, beans, tomatoes, seeds, onions, garlic, and potatoes.

In this experiment, the students observed changes in the food following exposure to different amounts of ionizing radiation. Intensity is directly proportional to the irradiation time. Experiments involving the sprouting of seeds and beans showed retardation of growth with longer irradiation times. Mold growth on cheese and bread showed a decline, and samples irradiated for five hours did not grow mold. Tomatoes and strawberries had a longer shelf life with an irradiation time of one hour. Students documented the procedures that were used and the changes that occurred in the food. They explained how and where their lab could be used in high school (biology, chemistry, physics, etc.), identified what students should look for and learn from this lab, and what questions could be asked after their experiment was completed.

Bacteria Cross-contamination

The "Simulated Salmonella Bacterial Contamination Laboratory" demonstrated how cross-contamination of salmonella bacteria can occur in the kitchen. The contamination was simulated by placing a chemical inside a whole fryer chicken. Students prepared the chicken, using techniques common in food preparation. A reagent that produces a color change when it comes in contact with the first chemical was sprayed over the preparation area. Cross-contamination was visible on utensils, the working station, and other foods. This has been a highly successful experiment as it demonstrated serious cross-contamination problems that can occur in the home. It also illustrated the need to reduce bacterial contamination in food products and the role that food irradiation can play in that process.

CHAPTER 4

FINDINGS AND RECOMMENDATIONS

The highly successful summer program has run for two years. Students suggested the program be longer, possibly three weeks in length. They further suggested that the time in class be increased by reducing the lunch and break periods. We consider these suggestions notable as they are not often heard from high school students. Laboratories were considered the most important element of the course. Field trips were also highly rated. All students in each of the courses said the summer program should continue.

Instructors recommended that because of high student interest, more student experiments related to contamination be added to the summer course next year. Participating teachers plan to include additional nuclear science units in their lesson plans at the high school level during the coming year.

Response to this year's solicitation was large enough that reservations for summer 1997 were taken and two new high school instructors have asked to participate. The program directors will investigate expanding the number of sections in order to meet the large demand by students and high school faculty.

APPENDIX A

COURSE SCHEDULE 1996

Day One

8:30-10:30	Classroom	Lecture on Radioactivity and Radioactive Decay
10:30-12:30	Laboratory	Geiger-Müller Working Region, Dead Time for a Counter
1:00-2:00	Laboratory	Data Analysis (Computer)
2:00-4:00	Classroom	Food Irradiation Experiment

Day Two

8:30-10:30	Classroom	Lecture on Half-life, Transmutation, Nuclear Dating, and Frequency Distribution
10:30-12:30	Laboratory	Thickness Gauging and Half-life
1:00-2:00	Laboratory	Data Analysis and Report Writing (Computer)
2:00-4:00	Library	Library Tour and Literature Research

Day Three

8:30-10:30	Classroom	Lecture on Food Irradiation
10:30-12:30	Laboratory	Simulation Salmonella Bacterial Contamination
1:00-2:00	Laboratory	Distance ($1/r^2$) and Frequency Distribution
2:00-4:00	Library	Literature Research

Day Four

8:30-10:30	Classroom	Lecture on Distance ($1/r^2$) and Frequency Distribution
10:30-12:30	Laboratory	Computer Data Analysis
1:00-2:00	Laboratory	Report Writing
2:00-4:00	Library	Literature Research

Day Five

8:30-10:30	Classroom	Lecture on Isotope Dilution Analysis and Liquid Scintillation
10:30-12:30	Laboratory	Unknown Volume Determination Using Isotope Dilution Analysis
1:00-2:00	Library	Literature Research
2:30-4:00	Laboratory	Report Writing

Day Six

8:30-10:30	Classroom	Lecture on Nuclear Reactions, Fission and Fusion
10:30-12:30	Laboratory	Cloud Chamber Experiment
1:00-4:00	Laboratory	Work on Projects (for presentations)

Day Seven

8:30-10:30	Classroom	Lecture on Radiation Safety
10:30-12:30	Laboratory	Contamination Demonstration
1:00-4:00	Laboratory	Finish Projects (for presentations)

Day Eight

	Tour	Super Nova Laser Facility (Lawrence Livermore Nuclear Laboratory)

Day Nine

	Tour (a.m.)	General Electric Nuclear Power Training Center
	Tour (p.m.)	Stanford Linear Accelerator

Day Ten

9:00-10:30	Classroom	Presentations
10:45-3:00	Classroom	Presentations/Lunch/Course Evaluation

APPENDIX B

LABORATORY EXPERIMENTS

Laboratory 1 - Geiger-Müller (G-M) Working Region

This experiment evaluates the limitations of the detector commonly known as a G-M detector. The detector is a tube, usually filled with argon and helium. The wall of the detector acts as a cathode, and a fine wire suspended in the center of the tube forms the anode. When radiation (alpha and beta particles) enters the G-M tube, some molecules in the tube are ionized. The negative ions move to the anode and the positively charged molecules move to the cathode, each creating a pulse that is counted and recorded.

The G-M tube has limitations. At low voltage, the tube is operating in an area of potential known as the "recombination region"; at high voltage, the tube is operating in an area called the "region of continuous discharge." In these two regions, the count rate of at different voltages is very unstable. The voltage that falls in between is considered "the working region" or the voltage at which the instrument should be operated.[54] Across this voltage range, the count rate forms a plateau where the count rate is least sensitive to changes in voltage.

<u>Experimental Procedure</u>[55]

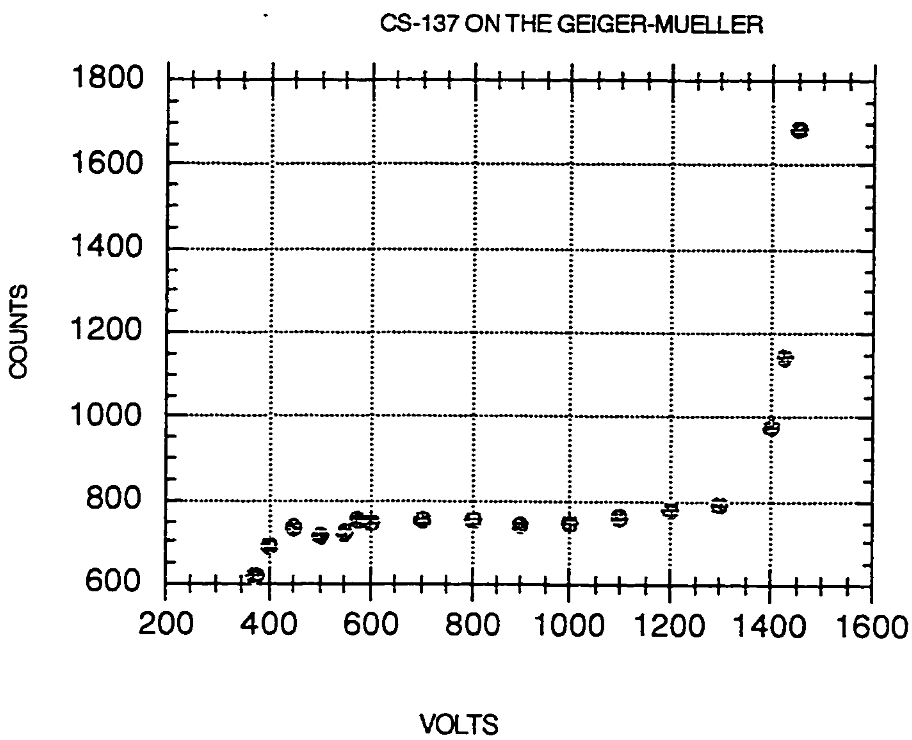
A G-M counting device and a long-lived source (i.e., ^{137}Cs) was needed for this experiment.

Check that the voltage controls on the high voltage module are set to zero and that the power switch for the module is OFF. Then, and only then, switch on the main power for NIM Bin (or counting assembly). Next, switch on the power switch for the high voltage unit and check to see if other units are operating correctly (scaler or counter, and the timer module). Obtain a standard source. Make a note of the number of the source and any distinguishing marks that will allow you to insert it into the holder with the same geometry every time.

Insert your source into the holder, close to the tube (top slot or second from the top). Turn the high voltage unit to 300 volts and take a 20-second count; increase the voltage by 50-volt increments and take 20-second counts until you have reached a plateau. Get into the habit of plotting the data when collected; do not merely form a table of values. Continue to increase the voltage in 50-volt increments until the end of the plateau has been reached and the count begins to deviate markedly from the flat plateau (the curve will rise sharply). Usual values for the plateau are in the range of 550 to 700 volts for the smaller type of detector tube (approximately 4" x 3/4" diameter), and in the range of 800 to 1,000 volts for the larger (6" x 1.5" diameter) tubes.

Do not raise the voltage more than 50 volts above the point where the curve rises sharply away from the plateau; this will cause the tube to go into a spontaneous discharge, corresponding to dielectric breakdown of the working gas (lightning discharge) that can damage the tube and the electronic circuits.

An example of the plotted results is as follows.



Laboratory 2 - Dead Time for a Counter

In this lab, students learn that the performance of instruments can degrade as the radiation intensity increases. The performance degrades due to a finite time the instrument uses to process a pulse created by a particle. During that time, other incident particles are not detected. The results in the failure to detect two occurrences that are closely spaced in time are considered "dead time." For the G-M counter, the source of "dead time" is the detector itself. The detector is "dead," or has a resolving time (t) of typically 100 to 200 microseconds. The simplest method to determine the detector's "dead time" is the paired-source method. This involves comparing the data collection rates for the combination of two radioactive sources to that of the sum for individual data collection rates. Dead time (t) can be solved using the following equation:

$$\text{Dead Time} = t = \frac{r_1+r_2-r_{1,2}-B}{(r_{1,2})^2-(r_1)^2-(r_2)^2}$$

where the true count rate for one source is r_1, the true count rate for a second source is r_2, the true count rate for both sources combined is $r_{1,2}$, and the true background rate is equal to B. The correction of "dead time" can now be accomplished by using the equation $n = m/(1-mt)$, where n is the true number of events, m represents the observed counting rate per second, and mt represents the total lost counting time per second. By adding the value of n (correction of counts per second) to the value of m (sample counts per second), the corrected count can be determined.

Experimental Procedures[56]

A G-M counting device and a split source supplied by the instructor will be needed for this experiment.

Using the given split source, carefully mount one-half of the source on a source holder specifically designed for this purpose. Mount one-half of the background source beside it to give a "complete" source with only one-half being radioactive. Be sure the sources are paired together so the asymmetric source-centers are adjacent under the G-M tube. Do not have the sources too close to the counter, or geometric problems will interfere with the dead-time determination. There should be approximately two cm between the G-M tube front face and the sources; this might correspond to shelf number two or three in the holder. Count this half of the composite split source.

Carefully, so as to retain exactly the same geometry, exchange the second half of the split source for the background half blank. Place the second half of the split source immediately alongside the first without disturbing the first half. Now count the combined split source. Remove the first half source, retaining the second half source in the same position. Place a half blank where the first half source was located and count only the second half of the composite split source. Use this information and obtain accurate values for r_1,

r_2, and $r_{1,2}$, and a value for the background B (both blanks inserted into the counter) that is statistically comparable to counting data.

Now, the given data points are r_1, r_2, $r_{1,2}$, and B. Convert all the counting data to counts per second, prior to any form of data handling. The units selected will dictate the final units of the dead time t. It is recommended that counts per second be chosen so that the final calculations for t lead directly to a value in seconds.

Data Handling

$$\text{Dead Time} = t = \frac{r_1+r_2-r_{1,2}-B}{(r_{1,2})^2-(r_1)^2-(r_2)^2}$$

$$n = m/1\text{-}mt$$

Finally, count rate m + n gives the corrected count rate.

Laboratory 3 - Thickness Gauging

An industrial application for the use of radionuclides is the gauging of the thickness of a material. For example, sheets of rolled steel with temperatures of over 1,000 degrees F at the rate of forty miles an hour would be very difficult to measure by normal procedures. However, a radioactive thickness gauge can determine the thickness on the basis that all matter will absorb radiation. The extent of absorption depends on the type of radiation used, the electron density of the material, and the compactness of the material. By predetermining the absorption of radiation at various distances via a calibration curve, the unknown thickness can be determined.

Experimental Procedure[57]

A ^{204}Tl source, a detector, plastic housing, and a timer-counter will be needed for this experiment.

Give instructions for starting the counter and reading counts.

Place the thallium in the second or third shelf of the plastic housing beneath the radiation detector which is connected to the timer-counter.

The equation for the beta decay of ^{204}Tl is:

$$^{204}_{81}Tl \rightarrow ^{204}_{82}Pb + \beta^-$$

Determine the activity of the sample in counts per minute (cpm) with no pieces of paper above the sample. Record this value in the data table.

Now, place a pad of five sheets of paper directly on top of the sample and record the cpm with radiation being absorbed by the paper. Repeat this procedure by adding five additional sheets of paper each time until there are a total of thirty-five sheets of paper. Record the data in the data table.

Plot the data on graph paper using the horizontal (x) axis for number of sheets of paper and the vertical (y) axis for cpm.

Provide students with a sealed package of paper of unknown thickness. Repeat the procedure for determining the cpm for this unknown thickness of paper. From the graph, determine the thickness of the pad of paper given as an unknown.

Laboratory 4 - Half-life

Half-life is the time required for the activity of a radionuclide to decrease by one-half. After one half-life, 50% of the original activity remains. After two half-lives, 25% of the original activity remains. After three half-lives, only 12.5% of the original activity is present, and so on.

The half-life of a nuclide can be derived by the equation $t_{1/2}=Ln^2/\Lambda$ where $t_{1/2}$ is the half-life, Ln2 is the natural log of 2 which equals (0.693), and Λ is the decay constant. The half-life of different nuclides ranges from less than 10^{-6} seconds to 10^{10}years. The value for half-life is often calculated for commonly used radionuclides.

When an unknown isotope is in question, the determination of its half-life is usually one of the first steps for identification. Determination of the half-life can be done by preparing a semi-log plot of its activity over a period of time. The complete time intervals of a short-lived nuclide can be observed directly. Very long half-lives are difficult to determine because a change of disintegration rate may not be noticeable in a reasonable period of time. In this case, a decay constant is calculated from an absolute decay rate, ($-dN/dt$-ΛN) where N is the absolute number of atoms in the sample:

$$N = \frac{6.02 \times 10^{23}}{\text{atomic weight radioisotope}} \times \text{mass of the radioisotope}$$

When the decay constant (λ) is known, the half-life can be calculated from the equation $t_{1/2}=Ln^2/\lambda$. The accuracy of calculating the half-life for very long-lived radioisotopes is determined by the accuracy of the decay constant. In this experiment, the half-life of an unknown foil will be determined using a Geiger-Müller (G-M) counter.

Experimental Procedure[58]

A G-M counting device and irradiated foil will be needed for this experiment.

Place the foils in a plutonium beryllium source for 30 minutes. Retrieve the foils and time the transfer from neutron activation to the G-M counter. The system is powered up to 900 volts, the working region of the system. Working in pairs, person number one reads the counts and restarts the instrument while person number two records the data. Fifteen readings of the sample at forty seconds per reading are taken with a twenty-second reset time, making each count at one-minute intervals.

After thirty minutes, measure the background. Repeat the process three times.

Laboratory 5 - Simulation Salmonella

Bacterial Contamination

Salmonella bacteria are often found in chicken. If handled improperly, they can contaminate surfaces, other foods, and utensils, resulting in various types of food poisoning. This poisoning has become a significant problem today. The number of victims affected by this bacteria increases annually in the United States alone. Many people who experience minor symptoms of food poisoning, diarrhea, and stomachaches, do not go to the doctor. The infections that warrant a visit to the doctor's office often go misdiagnosed unless a blood test or stool sample is taken to detect the bacteria.

More than 1,600 specific antigenic types of salmonella have been discovered, each carrying variations of the symptoms and severity of the disease. The pathogen causes three main disease in humans: enteric fever, septicemia, and gastroenteritis.[59] The different strains have incubation periods that vary from eight hours to twenty days and can cause anything from a stomachache to death.[60] Mild cases of salmonella poisoning are not chemically treated because at times the drugs can prolong the infection. Instead, the pathogen is allowed to run its natural course, passing in two to four days. During this time, the replacement of fluids and electrolytes is critical, especially in young children, the elderly, and people with the sickle cell trait or disease.

Once contaminated chicken reaches the market, salmonella continues to survive and thrive in temperatures above 37 degrees Fahrenheit and below 143 degrees Fahrenheit, which means that it can thrive in the refrigerator and in the oven if the chicken is not properly cooked.[61] The critical moment of continuing the spread of salmonella is the period in which the chicken is prepared and when the staples of the dinner are made, because although the bacteria on the chicken will be killed when it is thoroughly cooked, the knife, cutting board, and gloves remain contaminated.

Irradiation is one of several preventative measures that can hinder salmonella poisoning. The two most commonly utilized radioisotopes are ^{137}Cs and ^{60}Co. The ionizing radiation emitted removes electrons from their orbitals in atoms and molecules, destroying the pathogenic bacteria in food. The deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) of bacteria that control the life and reproduction of the microorganism are made up of very large and complicated macromolecules. Their large size makes them easy targets for gamma rays, and their complexity makes them highly sensitive to ionization. The slightest alteration in the molecular structure dramatically reduces the bacteria pathogenic potential.[62]

<u>Experimental Procedure</u>[63]

This experiment is a simulation demonstrating cross-contamination from poultry to other food items. Iron (III) sulfate [$Fe_2(SO_4)_3$] and potassium thiocyanate (KSCN) are employed to portray the contaminant spread of bacteria.

One whole chicken, a cutting board, a sharp knife, lettuce, carrots, mushrooms, apples, nectarines, bananas, salt and pepper, the chemical $Fe_2(SO_4)_3$ and KSCN (or dish soap with phosphorous and a black light), lab coats, gloves, and safety goggles will be needed for this experiment.

First put on all safety gear: goggles, apron, and gloves. Then set the chicken on a cutting board and remove the packaging. Place $Fe_2(SO_4)_3$ into the rear cavity of the chicken, where salmonella usually begins. Remove all internal organs and place them at the top of the cutting board. Using a sharp knife, remove the legs, wings, and thighs, and cut the body in half. Sprinkle the pieces with salt and pepper, and set them at the top of the board, next to the organs. Continue to use the same cutting board, gloves, and knife (without washing them) to slice and cut the other staples.

When all food preparation is finished, spray everything: food, tray, gloves, and utensils, with KSCN, which will turn any areas containing $Fe_2(SO_4)_3$ red. Observe the areas that have turned red and record the results. Once all observations have been logged, dispose of the chicken and gloves and wash the cutting board and utensils thoroughly.

An alternative method may be used if you do not wish to use the chemicals $Fe_2(SO_4)_3$ and KSCN. Use the same procedure, substituting dish soap containing phosphorous for $Fe_2(SO_4)_3$, and a black light for KSCN. Areas that glow under the black light are tainted.

The red or glowing areas are contaminated with salmonella, and persons that ingest those victuals will experience food poisoning.

Laboratory 6 - Distance ($1/r^{\wedge 2}$)

The intensity of radiation from a source decreases with distance. In theory, for a point source of radiation, the intensity should vary as the inverse square of its distance from a point detector. In reality, no source or detector is truly pointlike. For example, as a source becomes closer to the detector, the degree of correlation between the source and the detector increases greatly. At very short distances between a source and detector, count rates can be so high that dead time losses are large. However, when a source is at a very great distance from the detector, the count rate can drop rapidly due to beta particle absorption.

Experimental Procedure[64]

A G-M counting device and a standard source supplied by the instructor will be needed to complete this experiment.

Using the standard source supplied, obtain a count for the sample at each shelf height of the assembly. A 3 to 5% error in the count is acceptable. Measure the distance of the source, via the shelf slots, to the front face of the Geiger-Müller tube, and compile the data pairs for computation.

Plot the data on log-log paper, and from visual observation, determine the straight line portion of the graph. Use regression analysis to determine the slope of this portion of the curve, and hence a value for the index n in d^{-n}. Where computer software is available, fit a multiparameter curve to the experimental data, and submit a plot showing how well the power function (or power functions, if several orders of power function will fit the experimental data reasonably well) describes the displayed data.

Laboratory 7 - Frequency Distribution

The performance of Geiger-Müller radiation detectors can be evaluated by frequency distribution experiments. Frequency distribution is the organization of statistical data produced by dividing the range of values of the variable into classes and showing the frequency of each class. Data should fluctuate about a mean value; by plotting the frequency of occurrence of a value versus its value, a frequency distribution curve is produced. Frequency distribution experiments use long-lived radioactive nuclides for producing the "variable data." Radioactive decay is a random process. Using isotopes with very long half-lives gives a narrow range of random data. Counting the decay of the radioactive source using G-M counters provides counts of "natural fluctuations." The statistical fluctuation can be represented as a normal curve or Gaussian distribution. A Gaussian distribution has the following form:

$$P(x)=\{1/sqrt(2\pi\sigma^2)\}exp[-(x-x_{ave})2/(2\sigma^2)].$$

A broad base of the curve is an indication of a largely scattered distribution in comparison to a narrow base distribution curve. The distribution of an ideal instrument has a vary narrow distribution. Instruments with a wide distribution can be attributed to additional noise in a component of the instrument that results in skewed data. Another method for determining the performance of an instrument is by producing a time distribution plot, the value of a measurement versus time. The characterization of an instrument using a time distribution is accomplished by a "qualitative" study of the distributions. The frequencies should be random and flat (no slope). A slope could propose drifting of the experimental boundaries. Finally, the standard deviation of each instrument can be found. The instrument's standard deviation has the following form:

$$\sigma_{instrument}2=\sigma_{poisson}2-\sigma_{total}^2$$

where variance is σ^2 $_{poisson}$, and σ_{total} is the square root of the mean. In this experiment below, the performance of two instruments was determined by measuring their time and frequency distribution.

Experimental Procedure[65]

A G-M counting device and a long-lived radioactivity source, such as ^{137}Cs, will be needed to complete this experiment.

Place a radioactive source close to the window on the second shelf of the Geiger Müller tube. Power the system up to 650 volts, the working region of the system. Working in pairs, person number one reads the counts and restarts the instrument and person number two records the data. Take 250 readings of the sample at five-second time intervals. The five-second time interval allows a 3% relative error. Repeat the steps on a different Geiger-Müller detector. Plot data on the computer graph program. Analyze the data and compare the instruments.

Laboratory 8 - Unknown Volume Determination

Using Isotpe Dilution Analysis (DIDA)

There are three basic types of isotope dilution methods: direct, inverse, and double isotope dilutions. The methods use the same general principles, however, the procedure and techniques are allied under different circumstances. In the following activity, only the Direct Isotope Dilution Analysis (DIDA) will be considered. Direct isotope dilution measures the change of specific activity (the amount of radioactivity per given mass or volume of a sample) of a substance after its addition to a system containing an unknown amount.

A small predetermined volume of solution is extracted from the reservoir and counted to give its activity (SA_1). This is equivalent to taking a handful of red jelly beans, counting the handful, and finding you have ten. Then, an equivalent volume (V_1) of a "spike" with a known specific activity is added to the reservoir of unknown volume, thoroughly mixed, extracted once again to have the activity counted, and subtracted from the initial activity, giving (SA_2). This is like taking your handful of ten white jelly beans, your spike, putting them into the jar of red jelly beans, mixing, taking out a handful of ten jelly beans, and counting how many white ones you have compared to when you started. The unknown volume (V_2) can be determined by using the following equation: $V_1A_1 = V_2A_2$.

Experimental Procedure[66]

A one hundred µL pipet, a scintillation cocktail, ^{14}C or ^{3}H, four scintillation vials, and a liquid scintillation counting device will be needed for this experiment.

Prepare a radioactive reservoir to produce suitable beta or gamma-emissions, and determine the specific activity. Geiger-Müller counters, proportional counters, or liquid scintillation methods may be used for counting the specific activity of the radioactive reservoirs.

1. Pipet 100µL of ^{14}C into 10-ml of liquid scintillation cocktail. Count the activity "(SA_1)." Subtract background to acquire the INCREASE of activity of the unknown volume.

2. Pipet 100µL of unknown volume into 10-ml of ready-safe cocktail. Count the activity.

3. Pipet 100µL of (SA_1) into unknown volume. Count the activity. Subtract the background. The 100µL of (SA_1) is the initial volume (V_1).

By subtracting the counts from step three with the counts from step two, the increase of activity is acquired (SA_2).

Laboratory 9 - Cloud Chamber Experiment

Radioactive elements constantly undergo a process of radioactive decay at which time their nuclei emit high-speed particles and rays which are too small to be seen under a microscope. The cloud chamber is a device designed for the examination of the trails of radioactive emissions.

The examination is completed as follows: First, saturate the chamber with alcohol vapor. When the high-energy particles forge through the air, electrons are unleashed from some of the atoms and form ions. The ions must be stimulated by cooling the air to become a center for condensation. The alcohol vapor condenses on the ions, leaving a vapor trail which shows the path of the ray. Three types of rays are produced by a radioactive element: alpha particles, beta particles, and gamma rays.

Experimental Procedure[67]

A plastic cloud chamber (3¼" diameter), uranium ore (or other radioactive source), alcohol, dry ice, a magnet, and a lamp will be needed to complete this experiment.

Drench the felt band on the inside of the cloud chamber with alcohol, place the radioactive source on the bottom of the chamber, and cover the whole chamber. Place a slab of dry ice on a paper, and place the cloud chamber on the dry ice surface. When the air becomes saturated, observe the tracks of the particles. Use the magnet and watch its impact on the vapor trail tracks. The lamp should shine from above, down onto the black surface of the cloud chamber. Viewing will be better if the lights are turned off.

APPENDIX C

STUDENT COMMENTS AND RECOMMENDATIONS

In the final class evaluation, 100% of the students indicated that the Nuclear Science Outreach Program should continue. Students also made the following observations which will be used when planning the 1997 summer program.

Student Comments

"I really think that this course taught me more than I could have learned all year in a regular class."

"The library time was really useful, because I learned how to use it."

"I loved the labs; they were fun and I actually understood what I was doing and why."

"I really enjoyed this class; I definitely think it was worth waking up early in the morning, so I could attend."

"This class helped me think about my career aspirations."

"It was good to have several speakers."

"The field trips were fun and educational."

"This class will help me with my future physics classes."

"I like the way the labs tied in to everyday life (chicken lab)."

"The university labs gave me a chance to use the tools of the trade."

"I liked the trips to the Nuclear Reactor Power Plant and Lawrence Livermore Laboratory to see why we learned what we learned."

"One of the most useful things I learned in the class was how to use the library."

"The most useful parts of the class were the food contamination and fission units."

"This class proved my theory that all chemistry teachers tell corny jokes."

Student Recommendations

"We should have had a field trip each week rather than two during the last week."

"During the morning lectures, we should always have a break time."

"I didn't like doing our lab writeups as a team."

From "Glossary of Nuclear Science[68]

A-Bomb (obs., coll.) Atomic bomb. More properly, a nuclear bomb as the energy released is due to a nuclear process, not an atomic one. See *Nuclear Weapon.*

Absorb To combine radiation with an atom or nucleus. Photons (X-rays and gamma rays) are absorbed by excitation of nucleons or atomic electrons. Low energy electrons are absorbed by the atom, thereby ionizing it. When a nucleus absorbs a particle, it combines the particle and its energy with the other nucleons. This often changes the properties of the nucleus. The nuclide ^{2}H, for example, is a stable nuclide that becomes radioactive when it absorbs a neutron, forming ^{3}H.

Absorber Material that absorbs radiation.

Absorption The process of absorbing radiation.

Actinide Elements with atomic numbers 90 through 103 (Z=90-103), the elements that follow actinium in the periodic chart. The set of actinides includes the following elements: thorium (The), protactinium (Pa), uranium (U), neptunium (Np), plutonium (Pu), americium (Am), curium (Cm), berkelium (Bk), californium (Cf), einsteinium (Es), fermium (Fm), mendelevium (Md), nobelium (No), and lawrencium (Lr).

Activity Units: Becquerel (Bq). The rate of decay of a population of radioactive nuclides. Activity can also refer to the emission rate of a radiation from a sample, useful for samples with nuclides that emit multiple radiations per disintegration. (coll.) The dose rate of a sample

Alpha Decay Abbrev. α *decay*. Radioactive disintegration by emission of an alpha particle.

Alpha Decay, Half-life The half-life of a nuclide that decays by alpha emission depends on the energy released in that decay. Larger decay energies result in a shorter half-life. Geiger-Nuttal in 1911 developed a simple expression that relate the half-life and the decay energy: $\log \lambda = A \log R + B$, where λ is the decay constant of the nuclide, R is the range of the alpha particle (which is proportional to the energy), and A and B are constants.

Alpha Particle Abbrev. α. A ^{4}He nucleus; an isotope of helium with two protons and two neutrons. The term alpha is reserved for ^{4}He nuclei emitted during radioactive decay or as an ejectile in a nuclear reaction.

Atom The fundamental building block of matter. An atom consists of a small, dense nucleus surrounded by a cloud of electrons. The nucleus contains protons and neutrons that account for much of the atomic mass. Chemical properties are defined largely by the number of protons in the nucleus. An atom is said to be ionized when the number of electrons is not equivalent to the number of protons; the resulting electrical charge is the number of protons minus the number of electrons.

Atomic Bomb (obs.) More properly, a nuclear weapon as the energy released is due to a nuclear process, not an atomic one. See *Nuclear Weapon.*

Atomic Mass Unit Abbrev. *amu, u.* Fundamental unit of mass. Defined as 1/12 the mass of ^{12}C, the most abundant stable isotope of carbon. 1 amu = 1.660×10^{-27} kg.

Atomic Number The number of protons in a nucleus. Each atomic number represents a chemical element and is assigned a name and a symbol. A nuclide with 20 protons is an isotope of calcium and is represented by the symbol Ca. Atomic number is often represented by the symbol Z, for charge. Calcium is an element with Z=20.

Attenuate To reduce or diminish. Particles and photons can be attenuated by scattering the radiation out of a beam, by converting the radiation to another form (e.g., converting a photon through pair production into an electron-positron pair), or by an atom or nucleus absorbing the radiation.

Attenuation The process of attenuating radiation.

Attenuation Coefficient The rate at which the intensity of a radiation decreases or is absorbed in matter. If μ is the attenuation coefficient, and I_0 is the initial intensity of the radiation, then the intensity at some absorber thickness d is given by $I = I_0 e^{-\mu d}$. A related term is the absorption coefficient.

Background Radiation Ambient radiation; radiation that interferes with measurements. Cosmic rays and radioactivity in soil, water and air are forms of ambient radiation. This radiation is often a form of interference in measurements. Other forms of measurement background includes sources of radiation observable by the detector, contamination of samples, incomplete absorption of radiation in the detector or incomplete charge collection by the detector.

Becquerel Abbrev. *Bq*. Unit of radioactivity defined as 1.0 disintegrations per second.

Beta Decay Abbrev. *β decay, β^- decay, β^+ decay*. Disintegration by emission of a beta particle. (coll.) The emission of a negatively charged beta particle (electron or β^-). An antineutrino is also emitted in this type of decay and the decay results in the nucleus converting a neutron into a proton. Positron decay is a second type of beta decay and it refers to the emission of a positron (β^+), which is the antiparticle of the electron. A neutrino is emitted in the process and results in the nucleus converting a proton into a neutron.

Beta Particle Abbrev. β, β^-, β^+. An electron or positron (the antiparticle of the electron) emitted by a nucleus during radioactive decay.

Bq See *Becquerel.*

Breeder Reactor A nuclear reactor designed to produce more fuel (fissile material) than it consumes. Such reactors surround the fuel with a fertile (non-fissile) material that, when irradiated, produces fissile material.

Carbon-14 Abbrev. ^{14}C. A naturally occurring radioactive isotope of carbon that has a half-life of 5730 years. High-energy neutrons, produced in the upper atmosphere by cosmic ray interaction, react with ^{14}N to form ^{14}C through the (n,p) reaction. This radioactive carbon eventually mixes with carbon in the lower atmosphere, thereby making ^{14}C naturally available. Ancient sources of carbon, such as coal or petroleum deposits, are too old to contain ^{14}C: the radioactive carbon has decayed away.

Carbon Dating A method of determining the age of a biological sample. It is based on the known ^{14}C to stable carbon ratio that is maintained during the life of a plant or an animal. Upon death of the plant or animal, the ^{14}C concentration is not maintained but decreases with a half-life of 5730 years.

Chain Reaction A reaction whose products are capable of inducing further reactions. Neutron-induced fission is a common example. The fission reaction produces neutrons that can sustain the reaction, thus forming a "chain" of linked reactions. Energy of activation in the burning of a match is an example from chemistry. Striking the match produces the initial energy for the reaction to begin, and the energy released is sufficient to propagate the reaction.

Charged Particle A particle or ion that carries an electric charge.

Cloud Chamber A device for observing the interaction of radiation with matter. It consists of a container that holds a super-saturated vapor, such as water or alcohol. Radiation that passes through the container ionizes the gases, causing local condensation of the vapor. Multiple interactions of the radiation form tracks of condensation that are readily visible.

Cosmic Radiation Radiation from outer space. Cosmic rays.

Cosmic Rays Photons or particles from outer space. High-energy cosmic rays, with energies of 10^4-10^{10} GeV (billions of electron volts) originate from outside our solar system, while lower-energy cosmic rays ($^2 10^4$ GeV) our from our sun. Solar cosmic rays are primarily protons and helium.

Counter An instrument for recording the number of pulses from a detector. A synonym for counting system.

Counting Rate Units: counts per second (cps), counts per minute (cpm). The rate at which radiation events are recorded in a counting system. Counting rates do not include corrections for detection efficiency and geometry and are thus not identical to decay rates or emission rates.

Counting System A radiation detection system consisting of one or more detectors, electronics for processing the detector signals, output devices for displaying results, and computer hardware and software for recording and processing data.

Counting Time The period over which a radiation detector collects data.

Curie (obs.) Abbrev. *Ci.* Unit of radioactivity defined as 3.7×10^{10} Bq. Original definition was based on the amount of radon in equilibrium with 1 gram of radium.

Daughter The nuclide produced in radioactive decay. See also *Parent*.

Dead Time Time required for a detector and counting system to detect the interaction of a radiation with the detector, convert the deposited energy into an electrical signal, process that signal, and refresh the detection medium. The counting system is unable to process further events during this time and is said to be "dead".

Decay Chain A series of nuclides linked in a chain by radioactive decay. Each nuclide in the chain decays to the next until a stable nuclide is reached.

Decay Constant The proportionality constant of decay for a nuclide. It is related to the half-life by the expression $\lambda = \ln 2 / T_{1/2}$, where λ is the decay constant and $T_{1/2}$ is the half-life of the nuclide. A sample initially containing N_0 atoms of a particular radionuclide that has a decay constant of l will have an initial activity equivalent to $A_0 = dN/dt = - \lambda N_0$. Over time the activity will decrease as given by the expression $A = A_0 e^{-\lambda t}$.

Decay, Radioactive The spontaneous transformation of one nuclide into another by emission of particles, absorption of an orbital electron, or by fission. It also refers to gamma-ray and conversion electron emission that only reduces the excitation energy of the nucleus. Also called radioactive disintegration.

Decontamination Removal of unwanted contaminants from the surface of an object or from an area. Contaminants can be radioactive, chemical, or biological (as in bacterial and viral contamination). Decontamination is designed to reduce the risks of exposure.

Detector A device or material that is sensitive to radiation that can produce a signal which can be recorded. Photographic film is a simple detector. Other forms include gas-filled counters [Geiger-Müller or GM counters, proportional counters], crystal scintillators [sodium iodide or NaI(Tl) detectors], and semiconductor detectors [HpGe and Si(Li) detectors].

Detector, Geiger-Müller A gas ionization detector. Also known as GM detector. GM detectors consist of a tube containing a detection gas and electrodes. Radiations enter the tube through a thin window. The GM tubes are operated at a high electrical potential, allowing accelerated ions to produce the maximum secondary ionization. The ionization process is quenched when the extensive secondary ionization distorts the electric field. This results in an easily detectable pulse for even the weakest of radiations.

Detector, Ionization A device for detecting radiations. The detector consists of a chamber filled with an appropriate gas and electrodes maintained at a high potential. Ions are produced by the interaction of radiation with the gas. These ions drift to the electrodes, producing a measurable electric current.

Detector, Liquid Scintillation A device for measuring radiation. The radioactive material is placed in an appropriate liquid fluor. Interaction of radiation with the fluor produces fluorescent photons that are detected by photomultiplier tubes.

Deuterium (coll.) Abbrev. ^{2}H, *D*. An isotope of hydrogen which has a single proton and a single neutron. Deuterium is a stable, naturally occurring nuclide found with an abundance of 1 part in every 7,000 parts of ^{1}H. A deuterium nucleus is often referred to as a deuteron.

Deuteron (coll.) Abbrev. *d*. The nucleus of the ^{2}H atom. A deuterium nucleus.

Disintegration See *Radioactive Disintegration.*

Dry Deposition The process of removing particles from the atmosphere by impaction or gravitational settling.

Electromagnetic Radiation Photons. Radiation consisting of interacting electric and magnetic waves. Examples include gamma rays, X-rays, ultraviolet and visible light.

Electromagnetic Spectrum The range of energies, frequencies or wavelengths of electromagnetic radiation. The spectrum is often divided into the categories gamma rays, X-rays, ultraviolet light, visible light, infrared radiation, radio waves, television band, and microwaves.

Electron Abbrev. e^-. A basic constituent of atoms. Electrons travel in orbits around the atomic nuclei. They have a charge of -1 and a mass of $5.4858026(21)\times10^{-4}$ amu or 0.5110034(14) MeV.

Electron Capture Abbrev. *e^- capture, e^- capt., e^-c.* Radioactive disintegration by capture of an atomic electron. electron capture belongs to the general category of beta decay.

Electron Volt Abbrev. *eV*. Unit of energy. The energy required to raise an electron through a potential difference of 1 volt. 1 eV = $1.602189(5)\times10^{-12}$ erg.

Endoergic Processes that require the input of energy in order to be energetically feasible. Reactions and decays that have a negative Q-value are endoergic.

Energy The capacity for doing work.

Energy, Cosmic Radiation Most of the cosmic radiation has origins beyond our solar system and has an energy range of 10^{4}-10^{10} GeV (billions of electron volts). The sun produces a lower-energy spectrum of cosmic radiation, typically below 10^{4} GeV.

Excitation Addition of energy to a nucleus. This energy raises the system from one energy state to another. The term also applies to atomic and molecular systems.

Excited State States within a nucleus that lie at a higher energy than the ground state or lowest energy state.

Exoergic Processes would release energy if they proceeded and are thus energetically feasible. Reactions and decays with a positive Q-value are exoergic.

eV See *Electron Volt.*

Fallout Wet or dry deposition of airborne radioactivity. Fallout results from injection of radioactivity into the atmosphere due to accidents or nuclear explosions, and the subsequent attachment of that radioactivity to dust particles.

Fission Abbrev. *fis.* The process of splitting a heavy nucleus into two lighter nuclei. Considerable energy is released during fission. Spontaneous fission is a type of radioactive decay for some nuclides, such as ^{252}Cf. In other nuclides, fission is induced through the reaction of an incident radiation with the nucleus. Neutron-induced fission of ^{235}U is a common example which is used to produce electricity.

Fission, Induced Fission that is initiated by the absorption of a radiation by the fissile material. Neutron irradiation is used to induce the fission of ^{235}U.

Fission, Spontaneous Abbrev. *spont. fis.* Fission that occurs spontaneously, not induced by an incident particle. A type of radioactive decay.

Fission Yield Units: %. The probability of producing a nuclide in a mass chain from fission. Because a nucleus fissions forming two lighter nuclei, the sum of all fission yields is 200%.

Fluor A material that produces fluorescent radiation upon interaction with radiation.

Fusion The process of forming a heavier nucleus from two lighter ones.

Fusion Reactor A nuclear reactor that uses fusion reactions to produce energy.

Gamma Ray Electromagnetic radiation that is emitted by a nucleus with a very short wavelength. These radiations result from the de-excitation of an excited state in a nucleus. Individual gamma-ray quanta are also known as photons.

Geiger-Müller Counter See *Detector, Geiger-Müller.*

Geiger-Müller Detector See *Detector, Geiger-Müller.*

GM Counter See *Detector, Geiger-Müller.*

Ground State The lowest energy state of a nucleus, atom or molecule.

H-Bomb Hydrogen bomb.

Half-Life The time required for one half of a radioactive sample to decay.

Heat Exchanger Any device that transfers heat from one system to another. In a nuclear reactor, the heat exchanger transfers heat from the reactor cooling system to water that passes through the turbogenerators to produce electricity.

Hot (coll.) Highly radioactive.

Hydrogen Bomb Nuclear weapon whose energy is derived largely from fusion of deuterium (^{2}H) and tritium (^{3}H).

Induced Fission See *Fission, Induced.*

Induced Radioactivity Radioactivity that is produced by bombarding a substance with radiation. Irradiation of stable deuterium (^{2}H) with neutrons produces tritium (^{3}H) which is radioactive.

Inverse Square Law The intensity of a radiation field is inversely proportional to the distance from the source.

Ion An atom or molecule that has a non-zero electric charge.

Ion Chamber See *Detector, Ionization.*

Ionize To add or remove electrons from an atom, ion, or molecule, changing its electric charge.

Ionization The process of ionizing an atom, ion or molecule.

Ionization Detector See *Detector, Ionization.*

Ionizing Event An interaction of radiation that leads to the production of ions.

Ionizing Radiation Any electromagnetic or particulate radiation capable of producing ionization in matter.

Ion Pair A positive and negative ion having charges of the same magnitude. They are formed from the same atom or molecule through the interaction of radiation.

Irradiate To expose to radiation.

Irradiation The process of exposing to radiation.

Isobar Nuclides with the same number of total nucleons. ^{40}K, ^{40}Ca, and ^{40}Sc have 40 nucleons and are thus isobaric.

Isomer An excited state with a significant half-life. The definition of *significant* is arbitrary.

Isomeric State An isomer.

Isomeric Transition De-excitation of an isomer by gamma-ray or conversion electron emission.

Isotone Nuclides with the same number of neutrons. ^{14}C, ^{15}N, and ^{16}O have 8 neutrons and are thus isotones.

Isotope Nuclides with the same number of protons. Isotopes are the same chemical element. ^{5}Li, ^{6}Li, ^{7}Li, and ^{8}Li, all have 3 protons and are thus isotopes. Isotope is often incorrectly used in place of the term nuclide.

Isotope Dilution Analysis A method of using isotopic ratios for quantitative chemical analysis. The ratio of the concentration of two isotopes is compared before and after the addition of a known amount (a spike) of one isotope. This addition causes a change in the isotopic ratio that depends on the amount added, and the initial concentration of the element. Stable or radioactive isotopes of the element can be used as a spike.

Isotope Separation The process of increasing the isotopic concentration of a nuclide relative to other isotopes of that element. This produces one sample enriched in that isotope and another that is depleted in that isotope. The depleted sample is known as a tailing.

Isotopic Abundance Units: %. The concentration of one isotope in a sample relative to the other isotopes of that element.

Isotopic Enrichment The process of increasing the concentration of one isotope in a sample relative to that of the other isotopes of that element.

Isotopic Mass (coll.) The mass of a nuclide. Nuclidic mass is preferred as this is an improper use of the term isotope.

K-Capture A specific form of electron capture where the captured electron comes from the K shell (a 1s electron).

Kinetic Energy Energy due to motion.

Light Water Reactor Abbrev. *LWR.* A reactor that uses ordinary water as a moderator and a coolant.

LINAC Abbreviation for linear accelerator.

Linear Accelerator A device that accelerates particles down a long tube (or a series of tubes) by the application of oscillating electromagnetic fields.

LWR Light Water Reactor.

Manhattan Project (coll.) Manhattan Engineering District.

Manhattan Engineering District Code name for a U.S. War Department program during World War II. This program produced the first nuclear weapons, weapons exploded at Trinity (Alamogordo, New Mexico, USA); Hiroshima, Japan; and Nagasaki, Japan. The Atomic Energy Commission succeeded this military program on 1 January 1947. Common name is *Manhattan Project.*

Mass A measure of the energy content of matter. Often used as a synonym for weight.

Mass-Energy Relationship Albert Einstein stated in 1905 that mass is a measure of the energy content of matter. That mass is equivalent to energy is shown in the relationship $E=mc^2$, where m is the mass of an object, c is the speed of light, and E is the equivalent energy.

Mass Number The total number of protons and neutrons in a nucleus. The total number of nucleons. It is generally used, along with the chemical symbol two distinguish between nuclides. Tritium contains one proton and two neutrons and is represented by the symbol ^3H, where the mass number is 3.

Mass Spectrograph A device for separating ions on the basis of their mass and electric charge. Ions are separated by passage through the field of a magnet. The mass spectrograph is used to accurately determine the mass to charge ratio for nuclides (for mass measurements), to determine isotopic ratios, and for qualitative and quantitative chemical analysis.

Neutron Abbrev. *n*. A basic constituent of atomic nuclei. The number of neutrons in the nucleus defines the particular isotope of an element. Neutrons has zero charge and a mass of 1.008665012(37) amu or 939.5731(27) MeV. Free neutrons are produced in some beta decays and in fission. They are unstable, having a half-life of 10.39(20) min.

Nuclear Energy Energy released by radioactive decay or by a nuclear reactor.

Nuclear Explosion An explosion whose energy is derived primarily from uncontrolled nuclear fusion or fission chain reactions.

Nuclear Fusion See *Fusion*.

Nuclear Isomer See *Isomer*.

Nuclear Power Plant Any device that converts nuclear energy into electrical power. Many nuclear power plants use the energy from fission to produce steam (directly or indirectly) which drives a turboelectric generator thereby generating electricity.

Nuclear Reaction A reaction involving an atomic nucleus. It is usually initiated by bombarding a target nucleus with a radiation, called a projectile. The interaction of the radiation with the nucleus may cause the emission of other radiations, called ejectiles. In the reaction $^{14}N + n \rightarrow {}^{14}C + p$, the target nucleus is ^{14}N, the neutron is the projectile, and the proton is the ejectile. This reaction can also be written as $^{14}N(n,p)^{14}C$.

Nuclear Reactor A device in which a sustained fission reaction can be maintained. The core is made of a fissile material such as uranium enriched in the isotope ^{235}U. It is usually surrounded by water which moderates neutrons and removes heat from the core.

Nuclear Rocket A rocket engine in which the heat from a nuclear reactor superheats a propellant liquid. It is distinct from a chemical rocket that uses combustion to produce the heat. Nuclear rocket technology was studied in the 1960s but has not been put into use.

Nuclear Weapon A weapon whose destructive power is derived largely from a nuclear explosion.

Nucleon A proton or a neutron. the nuclides ^{3}H and ^{3}He both have three nucleons.

Nuclide A nucleus or a collection of nuclei with a specified number of protons and neutrons. Isotope is often (incorrectly) used for the term nuclide.

Nuclide Chart A graph showing all known nuclides. Each nuclide is represented on a proton versus neutron grid by a box that often contains a summary of basic properties. Nuclides are often colored on the basis of their half-life or primary mode of radioactive decay.

Orbit The region occupied by an atomic electron or by a nucleon in the nucleus.

Parent The first of two nuclides linked by radioactive decay. A parent decays to a daughter nuclide.

Particle Track The path along which ionization has occurred by the passage of a charged particle. Tracks can be transient as in a cloud chamber or they can be more permanent as in the decay of ^{238}U in a rock.

Photon A quantum of electromagnetic radiation, a gamma ray or an X-ray.

Plutonium Breeding A process of producing ^{239}Pu. The nuclide ^{238}U is irradiated with neutrons and then decays to ^{239}Pu.

Proton Abbrev. *p*. A basic constituent of atomic nuclei. The number of protons in the nucleus defines the element to which that nucleus belongs. The proton has a charge of +1 and a mass of 1.007276470(11) amu or 938.2796(27) MeV.

Pulse An electrical signal. It may result from the interaction of radiation in a detection medium or it may be produced by electronics in a counting system.

Pulse Height A measure of the amplitude of a signal. Generally used in the context of a detector signal where the amplitude is proportional to the ionization caused by an incident radiation.

Q-Value The energy that could be released in a nuclear reaction as calculated from the difference in total energy (including rest mass) of the products (product nuclei and ejectiles) and reactants (target nuclei and projectiles).

Quench To limit or stop a continuous discharge in a gas ionization detector.

Quench Gas A gas used in gas ionization detectors to quench continuous discharges. Alcohol, ether and methane are common quench gases.

Quenching The process of limiting or stopping a continuous discharge in a gas ionization detector.

Radiation Photons or energetic particles emitted during radioactive decay, by a device, or as ejectiles from nuclear reactions. Particles can take the form of electrons (beta particles), positrons, or light nuclei.

Radiations Specific types of radiations, such as X-rays, gamma rays, neutrons and protons.

Radiation Attenuation See *Attenuation*.

Radiation Shielding Attenuation of radiation by placing a shield of absorbing material between the radiation source and a person, or a device sensitive to radiation.

Radiation Source A radioactive sample or a device (e.g., accelerator, X-ray generator) that emits radiation.

Radiation Sterilization The process of exposing plants or animals to radiation making them incapable of reproduction. The process of exposing food or other objects to radiation, killing harmful bacteria and infestation.

Radiation Therapy The process of treating disease using radiation.

Radio- A prefix denoting a relationship to radiation or sources of radiation.

Radioactive Having the capacity to undergo spontaneous disintegration by the emission of radiation. Can refer to an atom, a collection of atoms or an object.

Radioactive Disintegration Spontaneous emission by a nucleus of photons or particles.

Radioisotope (obs.) Radionuclide.

Radionuclide A radioactive nuclide.

Radiotherapy Radiation therapy.

Radiotracer A radioactive nuclide as an ion or bound in a molecule that is used in a chemical, biological or other system to "trace" the pathways of that chemical. The radioactivity permits easy distinction between the nonradioactive element initially in the system and the radioactive tracer added to the system.

Radius, Nuclear The radius of a nucleus can be calculated from the simple expression $r = r_0 A^{1/3}$, where $r_0 = 1.3 \times 10^{-15}$ m (1.3 fm). Using this formula, the radius of a potassium nucleus is determined to be 4.41×10^{-15} m, compared to 2.31×10^{-10} m for the radius of the entire potassium atom.

Range Length of the track of a radiation in a medium. For ionizing radiation it can be defined as the length of path over which ionization occurs.

Range, Alpha Alpha particles interact strongly with matter. They can usually be stopped with only a single sheet of paper.

Range, Beta Beta particles interact less strongly with matter than alpha particles. They can usually be stopped by several mm of a light absorber such as aluminum.

Range, Gamma Gamma rays have a longer range than alpha and beta particles. They require several cm of heavier elements such as iron or lead to be effectively stopped.

Rate Meter An instrument that counts electrical pulses and displays the number of pulses per unit time.

Reactor (coll.) See *Nuclear Reactor.*

Recombination The process of neutralizing an ion pair.

Resolving Time Minimum time required following interaction of a radiation with a detector in order for a second radiation to be detected.

Saturation Current Charged particles produce an ionization upon interaction with the gas in a GM tube. Applying a potential across the gas produces a current as the ions migrate to the electrodes. At sufficiently high voltages, most of the ions are able to reach the electrodes. The current produced at these voltages is a saturation current.

Scaler An instrument for counting of pulses from radiation detection equipment. Scalers produce pulses that are proportional in number to the number of input pulses. Scaler is often a synonym for counter.

Scatter To change the trajectory of a particle or radiation.

Scattering A process that scatters a particle or radiation.

Scintillation Light produced by the interaction of ionizing radiation with a fluor.

Scintillation Counter See *Detector, Liquid Scintillation.*

Sealed Source Radioactive material enclosed in a package that is permeable to the radiation but prevents spread of the radioactivity. An example is ^{60}Co encased in a pellet of plastic. Sealed sources are used as radiation calibration standards.

Shield An absorber placed between a radioactive source and an object to reduce the intensity of radiation.

Shield, Biological A radiation absorbing material that reduces the exposure of radiation to personnel.

Shield, Thermal A heat-absorbing material used in a reactor to prevent overheating in the biological shield. It is usually made of thick metal plates.

Shielding A shield.

Source Material Any material that contains more than 0.05% of uranium, thorium, or a combination of both.

Special Theory Of Relativity A theory developed by Albert Einstein in 1905. Two consequences are the understanding that mass and energy are equivalent and that the mass of an object increases with its velocity.

Specific Activity The radioactivity of an isotope per unit weight of the element in a sample. The number of radioactive decays per unit mass of a sample.

Spectrum The intensity of a given type of radiation as a function of its wavelength, mass, or other related quantity.

Spike A sample of a nuclide or chemical added to a system.

Spontaneous Without an initiating force.

Spontaneous Fission See *Fission, Spontaneous.*

Stable Not radioactive. Incapable of spontaneous change.

Stable Isotope (coll.) A stable nuclide.

Stable Nuclide Strictly speaking, a nuclide that is not radioactive. The definition is often relaxed to include very long-lived nuclides that are naturally occurring. ^{209}Bi has a half-life of ^{3} 10^{19} years and is sometimes treated as stable.

Subatomic Particle Particles or radiation smaller than an atom. Protons, neutrons, electrons and mesons are examples.

Tag See *Tracer.*

Teletherapy Treatment by radiation from a powerful source located some distance from a body.

TNT Equivalent A measure of the energy released by an explosion. It is expressed as the amount of trinitrotoluene (TNT) that would release the equivalent energy. One ton of TNT produces 10^9 calories of energy.

Tracer A nuclide incorporated into a molecule to provide information on chemical processes and pathways. The tracer can be radioactive or an enriched stable isotope of an element. Also called a tag.

Transmutation Modifying the nucleus of an atom by bombardment with nuclear particles.

Tritium Abbrev. *^{3}H, T.* An isotope of hydrogen with a single proton and two neutrons. Tritium is radioactive with a half-life of 12.33 years. It is found in nature as a result of the interaction of cosmic rays in the upper atmosphere. A tritium nucleus is called a triton.

Triton Abbrev. *t*. The nucleus of tritium, ^{3}H.

Uranium Decay Series The nuclides fed in the radioactive decay of ^{238}U including all daughters through stable ^{206}Pb. Also known as the (4n+2) series because each member of the series has a mass equivalent to (4n+2), where n is an integer.

Uranium, Natural Occurrence The average concentration of uranium is soil is about 3 ppm.

X-Rays Photons or electromagnetic radiation produced by the de-excitation of bound atomic electrons. The energy of an x-ray is equivalent to the difference in energy of the initial and final atomic state minus the binding energy of the electron.

Yield Energy released in a nuclear explosion. See also *Fission Yield*.

Wet Deposition The process of washing out dust or other particles from the atmosphere due to rain.

Wilson Cloud Chamber (obs.) An early name for the cloud chamber, which was invented by C.T.R. Wilson in 1911.

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7 May 1997

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